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# Advanced Design of Complex Systems Using the Collaborative Visualization Environment (CoVE)

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## ABSTRACT

**This paper summarizes and introduces the Collaborative Visualization Environment (CoVE) at the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech. The CoVE is an advanced visualization facility consisting of an 18 ft x 10 ft display wall for high-resolution real-time visualization in support of collaborative design activities. Incorporating the latest advances in computing technology and graphics processing, the CoVE allows for the simultaneous display of a large amount of information and manages this information in a way that facilitates increased awareness of the design. Tools and techniques developed at ASDL not only increase the speed and fidelity of the design process but also allow for increased transparency of this process. For the first time, a sensitivity matrix with over sixty independent and dependent variables can be visualized simultaneously. This is in contrast to a typical display system where only about 15% of the information associated with a problem can be simultaneously visualized.**

**Since the CoVE was first activated in January 2004, it has been used by hundreds of engineers, technologists and decision makers from industry and government including General Electric, Pratt & Whitney, Raytheon, Boeing, Lockheed Martin, Rolls-Royce, NAVAIR, the Navy Labs, and NASA to name a few. Over 120 graduate students and 20 research engineers have utilized this advanced facility to demonstrate design tools and methods for a wide variety of unconventional, multi-mission systems. In 2005, the CoVE will be upgraded to include high-fidelity physics-based computing capability supported by Dell® high performance computing clusters. This technology will enable greater design space exploration and the analysis of technologies for large scale systems-of-systems.**

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## INTRODUCTION

The Collaborative Visualization Environment (CoVE) is a visualization facility sponsored by a 2004 award from the Office of Naval Research (ONR) through the Defense University Research Instrumentation Program (DURIP). The heart of the CoVE is a visualization wall that consists of twelve 67 inch rear projection display monitors linked together to provide a seamless video display with 4096 x 2304 resolution. The primary motivation for the creation of this research laboratory is to facilitate the display of massive amounts of information in a graphical and visual manner that encourages interaction during the design process by engineers and decision-makers. In addition to the primary display wall, the CoVE also features twelve computer workstations that allow participation by a number of students, engineers, and analysts. A plug-and-play interface has been designed that allows outside visitors to display information on the main wall without physically copying files or using shared network resources. This technique is useful, for example, when competitors at the subsystem level desire collaboration with a system integrator, but have concerns about data security in a networked environment. Using a touch-panel interface, space on the primary wall can be assigned by the session moderator to each of the twelve workstations or notebook computers. The CoVE also provides state-of-the-art video-conferencing capability to up to four simultaneous sites, and interfaces with television, VHS, and DVD systems.

An example of the CoVE environment during a recent graduate design competition review is shown in Figure 8. In this example, a morphing unmanned combat aerial vehicle (UCAV) design is proposed to representatives from an industry sponsor. The CoVE allows the simultaneous display of the House of Quality tool, morphological matrix, interactive multi-attribute decision making (MADM) tool, three-view drawing, interactive Pareto frontier evaluator, and Powerpoint® presentation. Additionally, a videoconferencing window is open in the bottom right-hand corner, and a video clip of a manned fighter intercepting a truck convoy is shown. The CoVE provides an unprecedented ability to visualize information and collaborate between multiple entities in the design process.

## APPLICATIONS AND DEVELOPMENT OF NEW METHODOLOGIES

The Aerospace Systems Design Laboratory (ASDL) is a research entity within the School of Aerospace Engineering at the Georgia Institute of Technology with a staff of 21 full time research engineers and over 140 master's and Ph.D. students. Each year, the incoming class of master's students participates in a series of design competitions for unconventional systems. The topics for the student competitions this year are as follows:

- Efficient Multi-Mach Vehicle: A 150-200 passenger subsonic/supersonic transport aircraft
- Two-stage-to-orbit turbine-based combined cycle access-to-space launch vehicle
- Morphing UCAV for attacking time-critical targets
- Long Range Liquid Booster Target Vehicle: a liquid propellant test asset for missile defense applications
- Multi-mission cruise missile capable of hypersonic dash and subsonic loiter for the interception of time critical targets
- High-altitude long endurance unmanned aerial vehicle for hurricane surveillance and homeland security

In addition to featuring unconventional systems for which there has been little previous research, all of the competitions in this effort involve multiple missions or morphing vehicles that must meet demanding and often disparate requirements. The final CAD models for the vehicles listed above are shown below in Figure 9. Since the CoVE facility became operational in January 2004, researchers and graduate students have greatly expanded the realm of collaborative design using this powerful visualization tool, and have developed a variety of new methods and techniques to convey information to decision makers at all levels.

For example, in these design efforts the House of Quality tool is used to translate the customer requirements into engineering characteristics. While this tool is critical in defining the problem, it is often created prior to meeting with the customer and a confirmation of the selected values is traditionally requested by the design team; however, since the design is largely driven by the importance weightings placed on the individual customer requirements, the design team can be limited by incorrect choices in the customer importance weightings at the beginning of the design effort. Using the CoVE, a tool was created in Microsoft Excel® that combines the House of Quality process with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) multi-attribute decision making methodology [1].

The House of Quality process provides the weighting values that TOPSIS then uses to rank any number of design concepts and reveal "the best" option to the design team, based upon the customer importance weightings. With the collaborative features of the CoVE and the large area available for visualization, a tool was developed that adds slide bars to the customer importance weightings, allowing the customer to alter these values in the presence of the design team. In this manner, customers are able to instantly see the impact of their changing requirements on the best option selected by the TOPSIS methodology. This method provides a stepping stone to the ultimate goal of conducting an electronic review in which the customer requirements remain variable until much later in the conceptual design process. An example of this tool is shown below in Figure 10. A portable and flexible version of this tool, the Interactive Concept Evaluation Environment (ICEE), incorporates probabilistic techniques into the dynamic House of Quality/TOPSIS downselect [2]. Instead of deterministic rankings of customer importance, it is possible to provide a distribution around a likely value using an Excel® add-in called Crystal Ball®. An example of one such input distribution for the "adequate payload" importance ranking is shown in Figure 1. Using a series of distributions on each of the customer requirements, the probabilistic simulation of the potential combinations of customer requirements can be executed in a matter of minutes on CoVE hardware. Macros have been created to automate the reduction of data and produce a chart similar to Figure 11. The probability density functions in this figure represent the overall goodness based on the specified distributions of the customer requirements. Areas of overlap indicate the degree to which the "best" option varies as a function of changing customer requirements. Using this technique, concept trade studies can be executed in real-time. The interactive nature of the

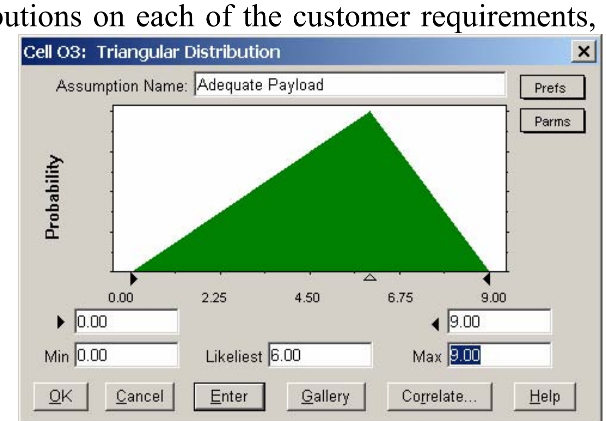


**Figure 1: Specification of the Triangular Distribution for Probabilistic Importance Assessments.**

ICEE allows decision makers to identify errors in the data set used for comparison, which were previously not visible to them. Also, unexpected results can indicate a missing customer requirement or engineering characteristic. Revealing these deficiencies enables more informed decisions and speeds up the time it takes to make them.

Another example of the use of the CoVE for collaborative design is through the examination of feasible design points using the Joint Probability Decision Making (JPDM) technique [3]. Through the use of surrogate models such as Response Surface Equations (RSEs), Neural Networks, Kriging Models, and other metamodels, many designs can be rapidly generated. The selection of an ideal point from this series of designs is often difficult due to the fact that a problem is rarely decomposed into a two or three dimensional problem. With the high resolution and large viewing area afforded by the CoVE, for the first time it is possible to examine the results from a JPDM exercise in multiple dimensions simultaneously. By generating multiple JPDM plots with different slices of the design space as shown in Figure 12, it is possible to highlight designs that satisfy the primary goals of the design project (in this case, $CO_2$ and $NO_x$ emissions), while examining where these points fall in the JPDM plots of other dimensions. Changing the color of these points instantly highlights them in every two dimensional slice of the design space as shown in Figure 12. In this manner, the viability of a region of feasible points can quickly be analyzed in a graphical and mathematical way [4]. Decision makers from NASA Glenn Research Center (GRC) used this technique for their 2004 Ultra Efficient Engine Technology (UEET) technology assessments and gap analysis for a 300 passenger commercial transport. Clicking a point showed the output characteristics of that design, such as aircraft weight, engine weight, $NO_x$ and $CO_2$ emissions, acquisition cost, RDT&E cost, and operating cost metrics. The independent design variables that create a given design can also be shown. Technologists present in the CoVE can comment on behaviors evident in the model and which physics-based causes contribute to these behaviors. Furthermore, a Java applet is employed to link each of the desired points to a conceptual flowpath diagram for the propulsion system produced by an integrated version of the NASA Numerical Propulsion System Simulator (NPSS) and Weight Analysis of Turbine Engines (WATE) aerothermodynamics and flowpath tools. Engineering judgment can be incorporated into the collaborative design process by allowing engineers and technologists to discuss whether a given conceptual flowpath seems reasonable.

Additionally, contour plots of the desired responses can be examined for the multiple dimensions of the problem. Shown below in Figure 2 is one such contour plot for an emissions reduction project. In the CoVE, up to sixteen of these three-dimensional plots can be viewed simultaneously. The plot can be rotated for viewing at different angles and the axes can be changed with a single click. Also, the contour plot updates instantly as different settings for the design variables are selected. The horizontal red plane represents a design constraint cutting through the contoured surface. Slide bars move the red constraint plane up and down to represent different goals. When the constraint plane does not cut

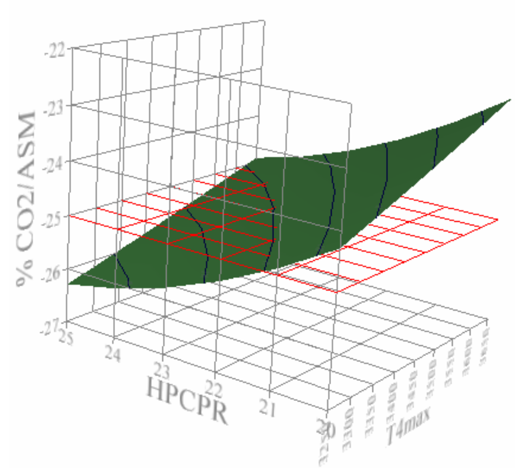


**Figure 2: Three-Dimensional Contour Plot for an Emissions Reduction Design Project.**

through the three-dimensional parametric design space, no solutions are feasible given that constraint. Using this technique, it is easy to identify the trends in the design and determine what decisions need to be made in order to satisfy the constraints. In the graphical environment, constraints can easily be changed to demonstrate the impact of changing customer requirements and the assessment of future goals.

With advances in rapid design methodologies, new capabilities have become available for the integration of geometry and vehicle analysis. Using these techniques in combination with a genetic algorithm, vehicles that satisfy mission requirements can quickly be generated and analyzed within a physics-based design environment. However, one major drawback to this approach is that computerized systems possess no engineering intuition and therefore produce designs that are technically feasible but are unrealistic based on experience. This shortcoming is due to the fact that some design constraints exist that cannot be accurately modeled within a computerized conceptual design environment. With the CoVE environment, this technique is modified to include a “man-in-the-loop genetic algorithm” where an experienced engineer can eliminate infeasible options by selecting a region of undesirable designs or features which he or she deems to be unrealistic. The algorithm will then ignore technically feasible options which are generated by the genetic algorithm but fall within the constraint space as specified by the designer. An example of twenty design concepts for a supersonic business jet is shown in Figure 3. All of the vehicles in the above example have a complete propulsion cycle analysis performed using NPSS, an accurate engine weight estimated from WATE, a first-order aerodynamic analysis verified with a CFD pass at certain altitudes, and are fuel-balanced for the given mission according to the NASA synthesis and sizing code FLOPS. The number of concepts generated depends on the time available for the study and the desired fidelity of the problem. In this case, the number of CFD runs desired greatly limits the number of candidate designs that can be examined. The red-circled design indicates a configuration which is technically feasible, but is not desirable based on engineering judgment. By selecting eliminating this design from the genetic algorithm selection pool the optimized solution will tend to move away from this type of design.

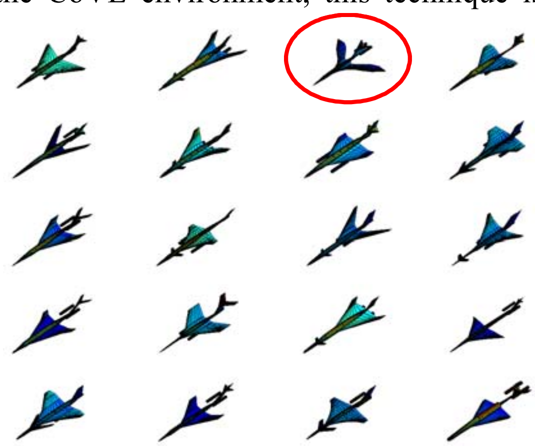

**Figure 3: Results of a Genetic Algorithm Exploration for Potential Supersonic Business Jet Configurations.**

The interactive nature of the CoVE was further used to perform a trade study between subsonic loiter time and supersonic cruise Mach number for a morphing unmanned combat aerial vehicle (UCAV). This tradeoff environment is shown in Figure 13. Slide bars are again utilized in this Microsoft Excel®-based example. The diamonds in the figure represent aircraft that utilize morphing technology, while the triangles represent conventional configurations. In general, morphing aircraft form the boundary of the Pareto frontier. As a slide bar is moved to one extreme, the Pareto frontier decomposes into solutions that are conventionally dominated, either as supersonic cruising vehicles with little loiter ability (essentially cruise missiles), or as long-loiter aircraft with limited attack speed like the Global Hawk UAV. When the slide bars are set to an intermediate condition, the need for morphing technology is reinforced. This environment graphically manipulates the technology gap between conventional and morphing aircraft based upon changing customer requirements.

Although the CoVE provides the ability to integrate these tools and methods in a novel way, some collaboration partners may not have access to the software tools required for rapid geometric modeling, multivariate regression, creation of neural networks, evaluation of JPDM relationships, or probabilistic modeling. To this end, the Java-based VistaVISION framework was developed. VistaVISION, shown in Figure 14 contains the necessary components to execute the aforementioned techniques, but is portable to any computer that runs Windows® and contains a freely-available Java runtime environment. A key feature of this framework is that the response surface equations for the evaluation of the design are tied to the geometry of the vehicle. Moving the hairlines at the bottom of the screen is equivalent to changing the independent design variables. When the hairlines are moved, the responses are instantly updated and the simple geometry model is modified to reflect the new design point. Constraints can be added to any response and moved with slide bars to represent different goals. An example of this interactive feature is shown below in Figure 4. VistaVISION also enables probabilistic analysis to model the uncertainty for a given target and contains a JPDM environment that duplicates the functionality of commercially available tools. When constraints are added, infeasible points in the JPDM "constellation" are highlighted in red so that distinct regions of interest can be rapidly identified. An example of this technique is shown in Figure 5. A graphical interface allows decision makers to change the axes. Constraints can rapidly be turned on or off to gauge the sensitivity of the design space to decisions made using the interactive environment. The VistaVISION software can be copied onto a CD following an electronic review so that decision makers can later use the environment to perform follow-up trade studies starting from the selected baseline.

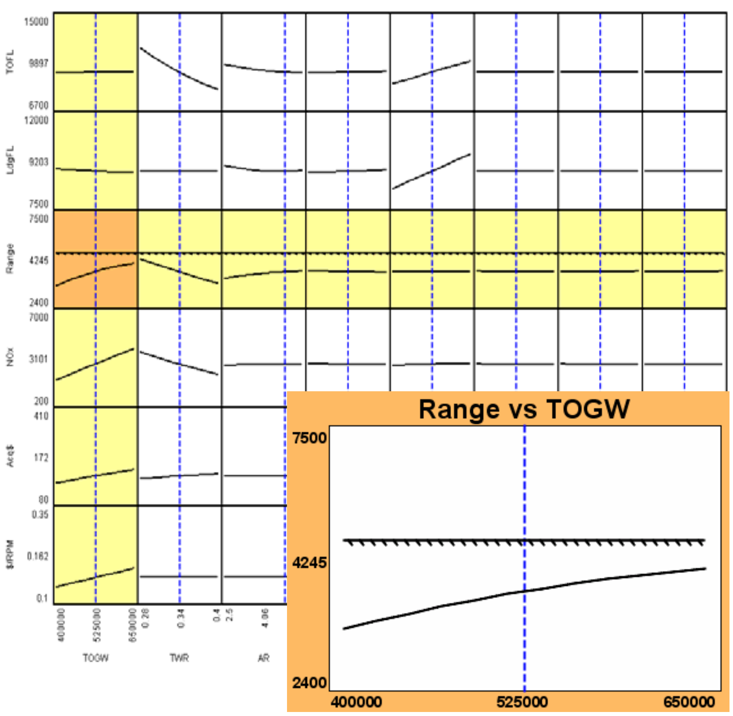


**Figure 4: Interactive Prediction Profiler Using VistaVISION.**

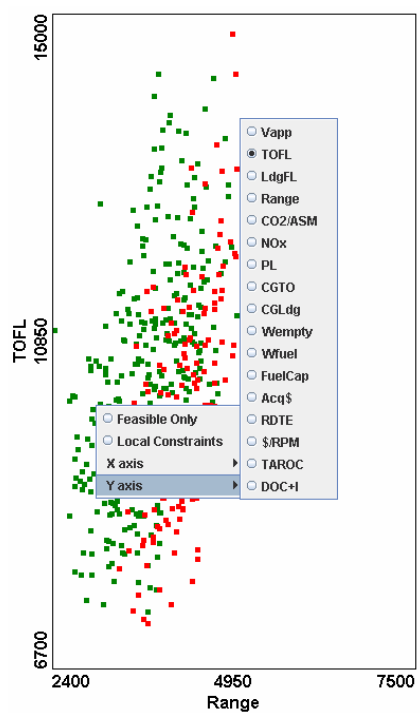


**Figure 5: Joint Probability Concept Exploration Using VistaVISION.**

## DISTRIBUTED HIGH-FIDELITY PHYSICS-BASED COMPUTING

Another major thrust of this research effort is the increased desire to use higher-fidelity physics-based design codes in the conceptual design phase. Reduced reliance on historical data and a thorough understanding of the physics of the problem is required to ensure that unconventional systems are correctly modeled. The synthesis and sizing-centric design process involves the linking of each of the traditional disciplines to a single controlling routine as shown in Figure 6. The inner circle represents conceptual design tools that are very rapid and efficient but may lack fidelity. The outer circle indicates tools that have a higher level of fidelity, but are traditionally more difficult to integrate and require more computing power to execute. Current research efforts involve using advanced techniques to allow high-fidelity tools to be integrated into the earlier phases of design.

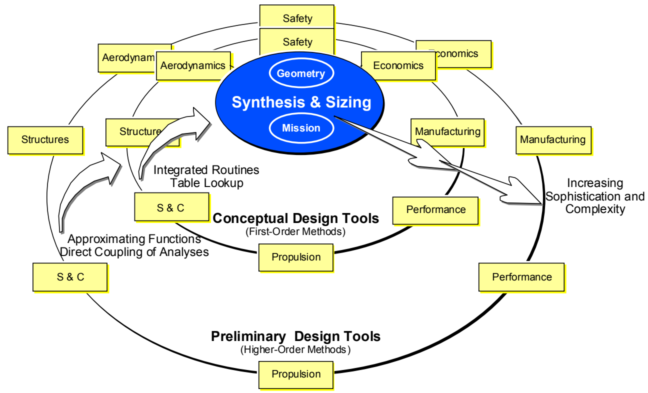


**Figure 6: Variable Fidelity Modeling and Simulation Environment.**

To support this effort, ASDL researchers are utilizing a new multidisciplinary optimization framework called the Federated Intelligent Product Environment (FIPER). The FIPER project is a four year research effort co-sponsored by the National Institute for Standards and Technology (NIST), General Electric, Goodrich, and several other partners from industry and government. At the conclusion of the pilot project in December 2003, FIPER was commercialized by Engineous Software into an infrastructure that supports collaborative design across organizational boundaries. Using the CoVE as the “control center” for a collaborative effort, individuals from different entities in geographically distributed locations can participate in a collaborative design. With the security provided by the FIPER environment, data can be passed between entities and across institutional firewalls to allow the designers at the CoVE to access required design codes without requiring physical ownership of those codes.

A notional example of such collaboration is shown in Figure 15 [5]. In this instance, researchers from NASA Langley Research Center, operating from the CoVE, can access CFD codes at their home base, as well as emissions codes from NASA Glenn Research Center and proprietary engine and airframe models from General Electric and Boeing respectively. Secure transfer protocols ensure that proprietary data is protected and restricted computer codes never leave their home facility, meaning that security measures already in place at those facilities are maintained, thus reducing the overhead costs associated with releasing actual codes to other entities. With the advanced videoconferencing abilities of the CoVE, it is possible to receive design input from discipline-level experts at those facilities. The elimination of travel time to a central location and the setup time required to transfer codes to external systems means that a greater portion of the design cycle time can be dedicated to design efforts. Also, discipline-level experts maintain ownership of their codes and version control is preserved due to the fact that the design team at Georgia Tech is always using the most current version of a code on the host entity’s local computer. Additionally, several collaborative partners have highlighted the information technology barriers to collaborative design as being major roadblocks to integrated product and process development. In some instances, subsystem manufacturers must ship a specially configured computer to the system integrator. In other instances, this computer system also requires a specialized engineer to be assigned to the remote site for the duration of the project. FIPER, and similar systems in development by other product integration and design optimization companies, may enable a transition to a fully-integrated collaborative design. Ongoing research at ASDL is addressing the distribution of design codes over a local network using internally created distribution algorithms or Grid computing "middleware" provided by IBM.

Finally, alliances between organizations change rapidly, and a major security concern is the release of proprietary information to an entity that may not be "friendly" in the future. Using a collaborative environment, host entities can discontinue access at any time, preserving security and all proprietary information. The ability to perform this type of design eliminates one of the major obstacles to a collaborative effort: the fear that proprietary codes and data can be released to entities not approved by the sponsoring company.

## FUTURE WORK

Advances in design methods provide reductions in cycle time and allow the examination of larger portions of the design space; however, the inclusion of higher-fidelity analysis tools in the conceptual design process will likely require an increase in computational power. In April 2004, the ASDL was awarded a second DURIP award from the Department of Defense (DoD) and the Office of Naval Research to fund the acquisition of advanced computational capabilities. As a result of this award, the physics-based computational capability of the CoVE is supported by a high performance computer cluster comprising 128 Dell® PowerEdge™ 1850 servers with dual, Xeon 32-bit/64-bit, 3.2 GHz processors with 4GB of memory. The cluster has approximately 6.7 terabytes of storage and high-speed interconnect for the cluster is achieved using a Topspin® Infiniband architecture [6,7]. The system supports true parallel processing and distributed computing-type applications. The cluster also has full tape backup capability to safeguard the data and information stored on its hard drives. For problems with high dimensionality, this hardware will facilitate the exploration of the extremes of the design space and supercomputer time to generate response surface equations.

The future vision for how the CoVE will be used for collaborative design is enhanced by the addition of a sister facility next to the visualization environment. The CoVE hardware will be primarily used to support reviews and collaborative activities that require advanced visualization. The design of the actual systems will be supported by the new facility, the Collaborative Design Environment (CoDE). Modeled after the "war rooms" from JPL's Team X, United Technology Research Center, and Airbus, the CoDE is an environment designed to foster cross-disciplinary Integrated Product Teams (IPT's). Although the layout of the CoDE is reconfigurable for a variety of scenarios, the basic layouts of the CoVE and the CoDE are shown in Figure 16. The room is designed to function as a central meeting room for up to twenty-four team members, or to split into as many as four smaller areas for subteams or competing teams. Video linkages to the CoVE and smartboard technology will allow instant communication between the decision-makers in the CoVE and the background engineers and technologists in the CoDE. During a collaborative design activity, assumptions can be revised by managers in the CoVE, while computer models are updated in real-time by the disciplinary experts stationed in the CoDE backroom. Georgia Tech's supercomputing assets and parallel computing facilities will be utilized to rapidly update the surrogate models used by the CoVE. Disciplinary experts can also help with integration techniques and validate the solutions provided by optimization algorithms.

The CoDE will also serve as a testbed for advanced data management and process design techniques. A software tool called the Architecture for Information Systems (ARIS) by IDS Scheer is a knowledge management tool that facilitates real-time electronic reviews. After outlining a process using traditional flowcharting tools, ARIS allows files to be attached to various steps of the process. For example, by clicking on a step like the "House of Quality", as shown in Figure 7, the appropriate software is opened and the model is loaded. Design team members can view the document, make changes, and publish this document out to a shared network resource for other team members. Instead of preparing a Powerpoint® presentation for a critical design review, engineers can simply load the ARIS tool and show the current state of the art. By linking directly to the CoVE for visualization, the desired pieces can be assembled in real-time and trade studies can be performed with actual data using high-fidelity physics-based tools as required by the study. Additional techniques to be explored include the use of middleware-enabled integration with tablet PC's, touch-screen monitors, and handheld devices. Through a Bluetooth® or radio-frequency identification (RFID) communications system, a lead engineer can walk through the CoDE between cross-functional teams and receive instant updates to his/her tablet PC or PDA. Wireless internet and cell-phone integrated technology will keep the lead engineer connected to his team regardless of where he is in the world. This technology not only enables enhanced communication for the design community, but also forces a change in business behavior: instead of sneaking out of a meeting to make a cell-phone call, a manager's scribbled request on his PDA can instantly be sent back to the CoDE where engineers prepare the necessary data and beam it back to the manager's laptop. Although these techniques have been demonstrated in a limited way in the retail sales industry by giants such as Wal Mart, engineering firms have been reluctant to embrace this advanced technology because they have not yet seen the power of "enhanced design awareness."

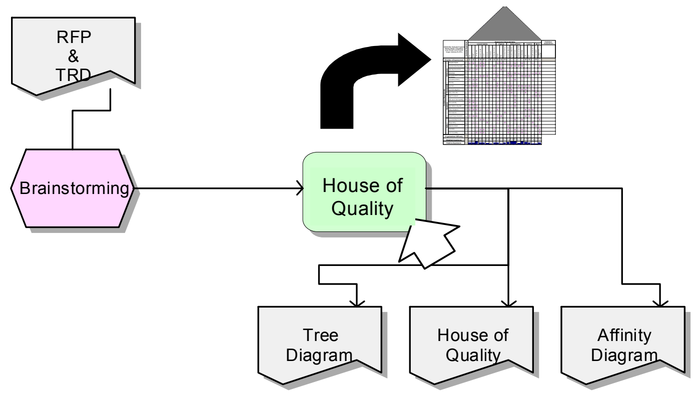


**Figure 7: Architecture for Information Systems (ARIS).**

## CONCLUSIONS

The Collaborative Visualization Environment (CoVE), sponsored by the Office of Naval Research is a unique facility that provides an ideal environment for interactive design activities and provides an environment where decision makers can meet to discuss relevant problems facing any discipline. When combined with the Collaborative Design Environment (CoDE), the Georgia Tech ASDL will be able to serve a variety of unique needs for high-fidelity physics-based computing and interactive design. ASDL advances in design methods for complex systems and systems-of-systems can be demonstrated in this environment, and the CoVE/CoDE combination serve as the ideal testbed for advanced design and management techniques. Through experience with many unconventional systems from aircraft, missiles, hypersonic vehicles, personal air vehicles, military systems, and systems-of-systems, the Georgia Tech ASDL is ideally poised to perform technology and system assessments across a wide range of platforms. The CoVE represents the next step in collaborative, multi-site design and will catalyze a new paradigm shift to a more transparent and thorough conceptual design process.

## REFERENCES


1. Hwang, C.-L., Yoon, K., Multiple Attribute Decision Making: Methods and Applications: A State-of-the-Art Survey, Springer-Verlag, Berlin, 1981.

2. Biltgen, P., "Concept Identification and Selection Methods for a Solid-Propellant Target Vehicle to Support the Development of a National Missile Defense (NMD) System," AE 8900 Special Projects Report, Georgia Institute of Technology, August 2004.

3. Bandte, O., Mavris, D.N., DeLaurentis, D.A., "Viable Designs Through a Joint Probabilistic Estimation Technique," Presented at the 4th World Aviation Congress and Exposition, San Francisco, CA, October 19-21, 1999.

4. Kirby, M.R., Rupp, J., and Mavris, D.N., "An Approach for the Strategic Planning of Future Technology Portfolios." SAE 2004-01-3109, Presented at the World Aviation Congress, Reno, NV, November 2-4, 2004.

5. Biltgen, P., Mavris, D.N., "Advanced Design Using FIPER and the Collaborative Visualization Environment" Presented at the Engineous User's Conference, Atlanta, GA, October 29, 2004.

6. Dell Corporation, "Dell® Poweredge™ 1850 Product Information Sheet," http://www.dell.com/downloads/global/products/pedge/en/1850_specs.pdf, Last Accessed November 2, 2004

7. TOPSPIN Communications, Inc., "High Performance Computing Applications Technical Note," http://www.topspin.com/solutions/hpc.html, Last Accessed November 2, 2004.


**Figure 8: CoVE Environment During a Design Review.**

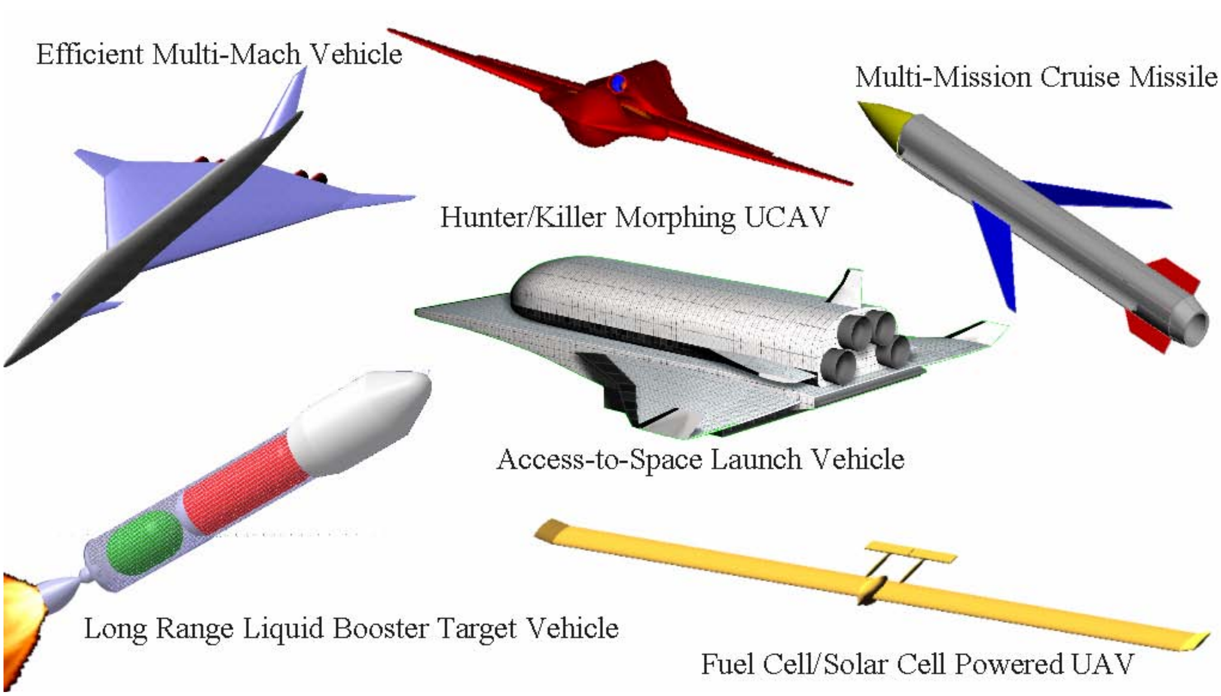


**Figure 9: Example of Six Unconventional Systems Designed by First-Year Graduate Students at the Georgia Tech Aerospace Systems Design Laboratory.**

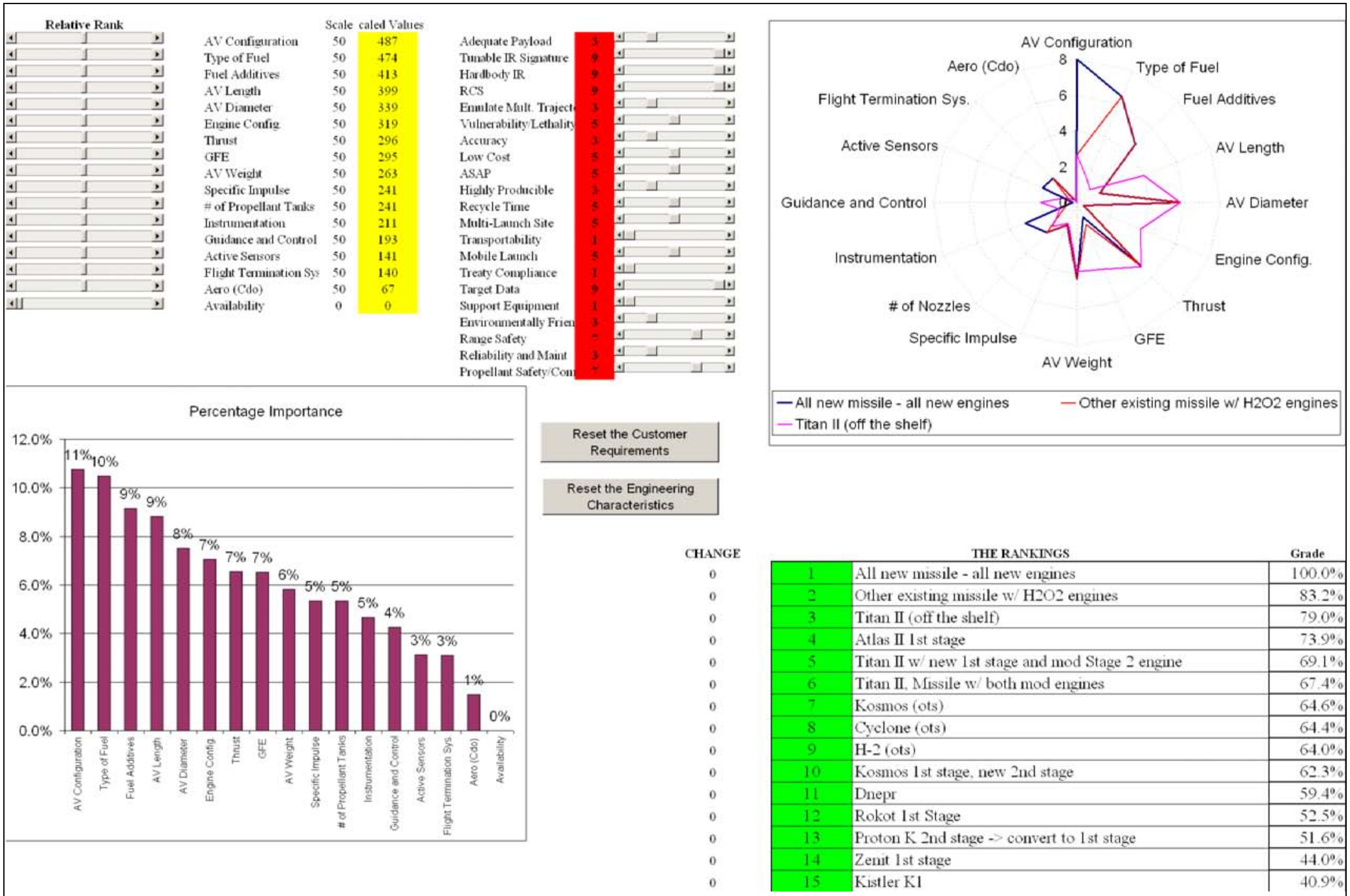


**Figure 10: Interactive Concept Evaluation Environment (ICEE).**

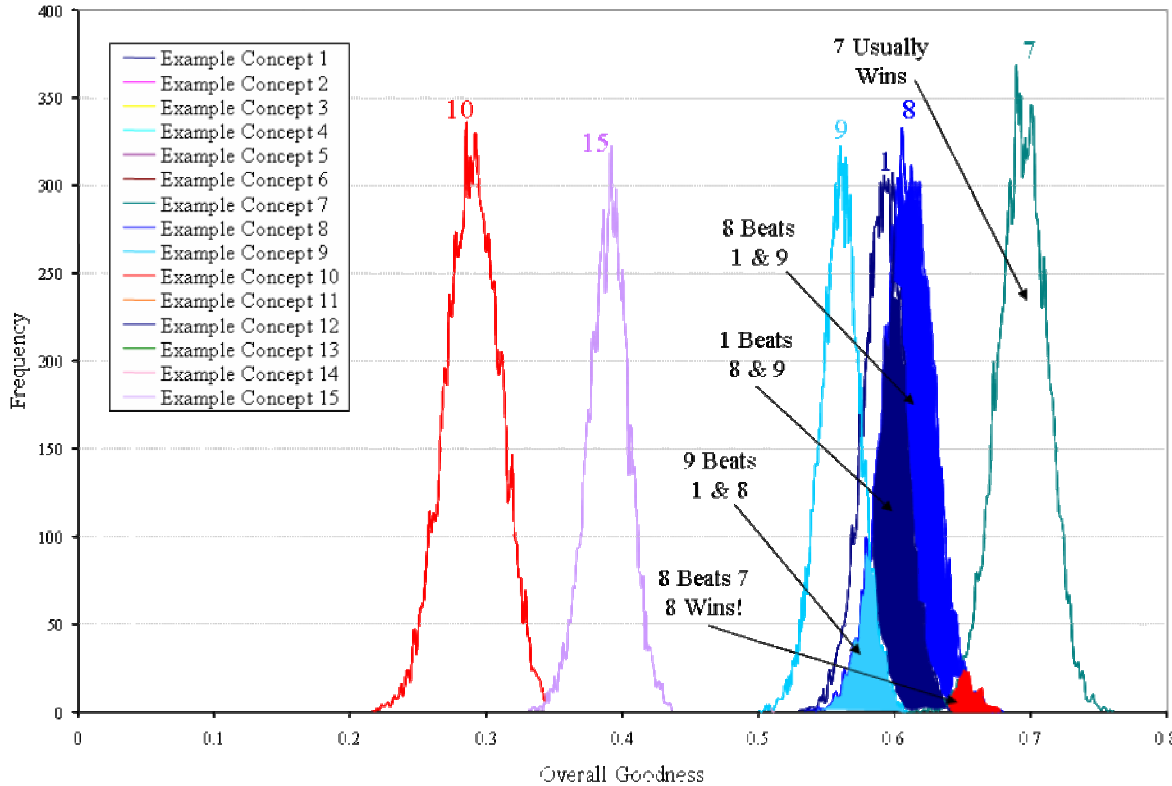


**Figure 11: Probabilistic Concept Evaluation Using the Interactive Concept Evaluation Environment (ICEE).**

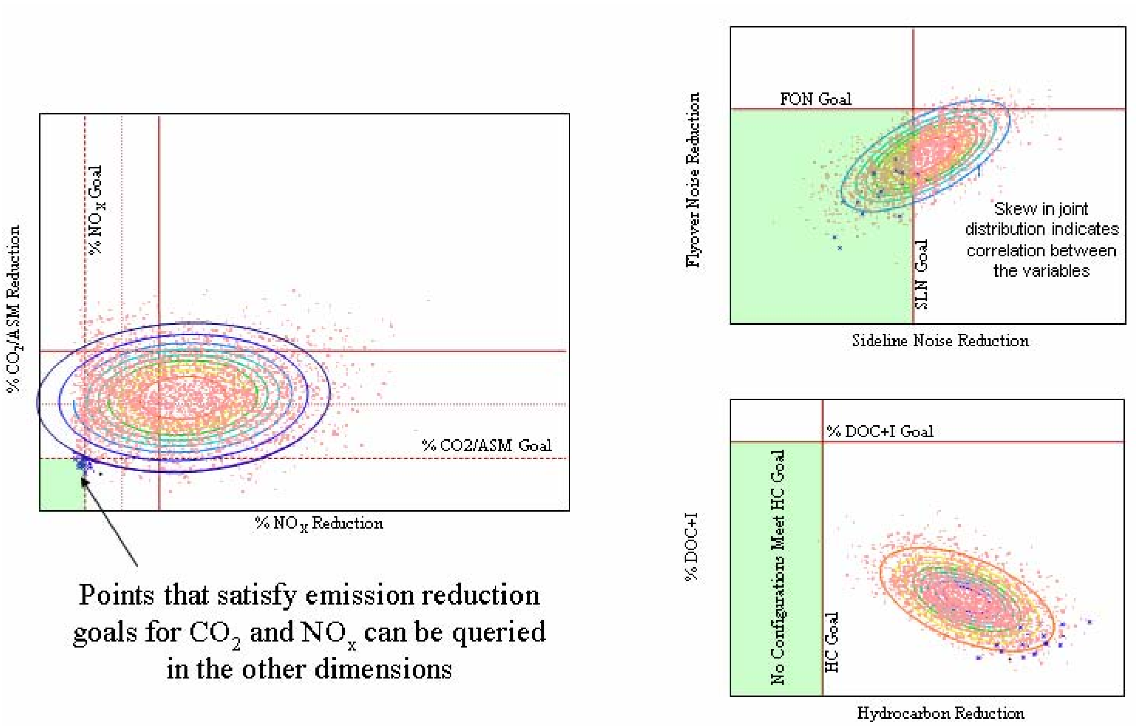


**Figure 12: Selecting Viable Design Points Using the Joint Probability Decision Making (JPDM) Approach.**

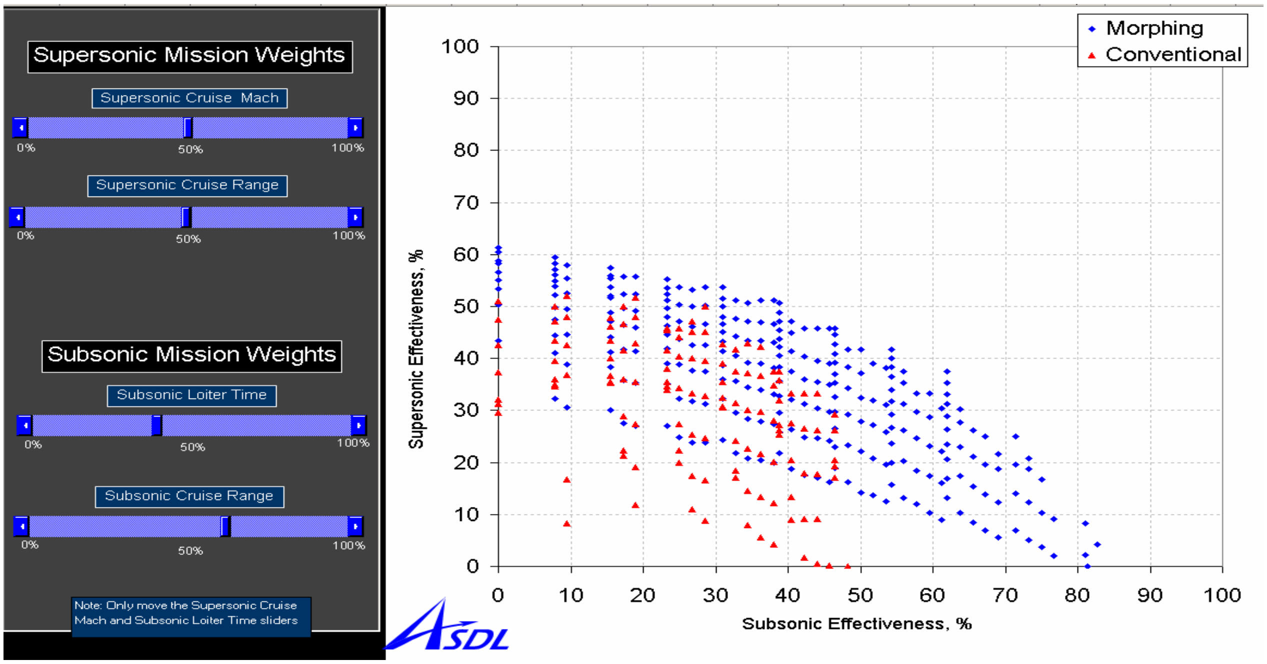


**Figure 13: Dynamic Pareto Frontier for a Morphing Unmanned Combat Aerial Vehicle (UCAV).**

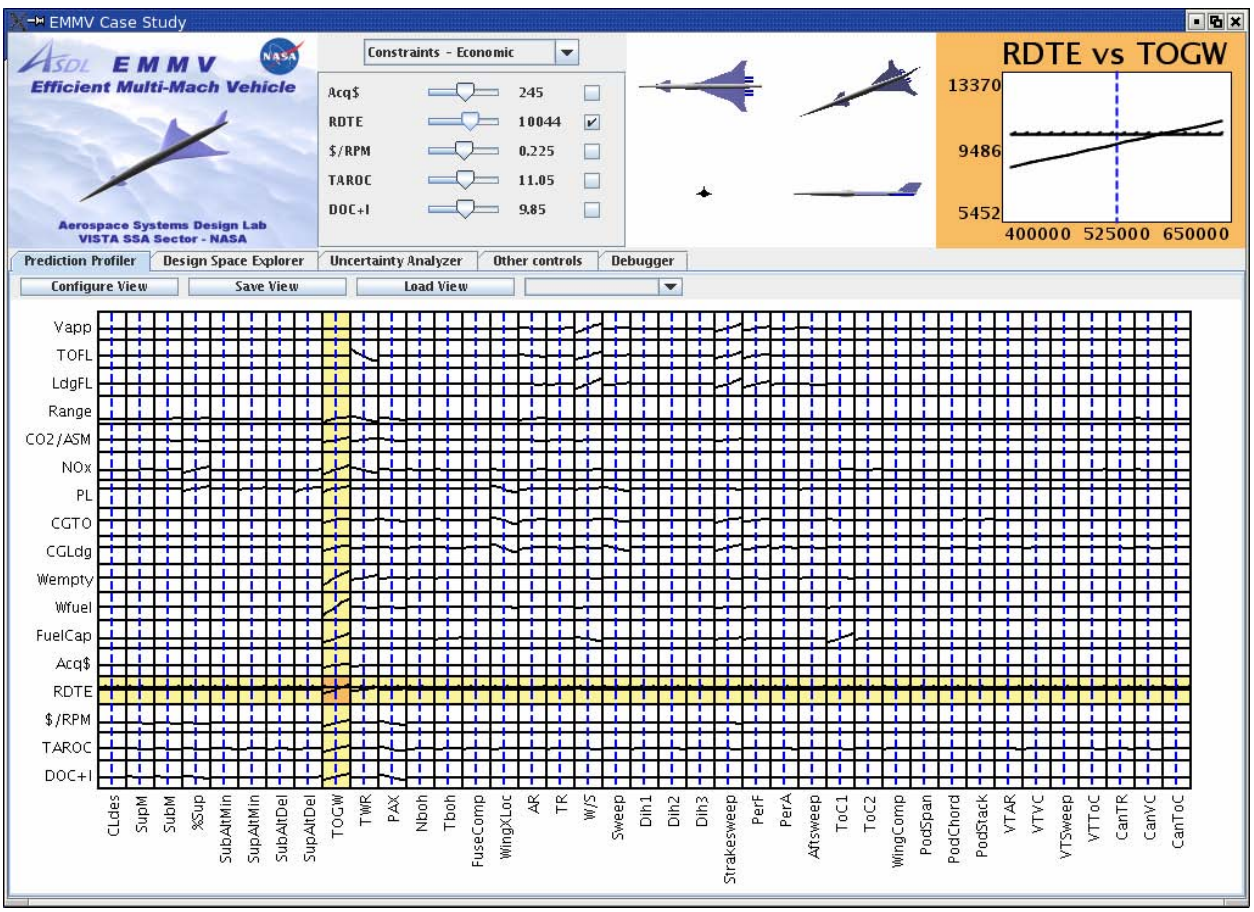


**Figure 14: VistaVision Environment for a Supersonic Transport.**

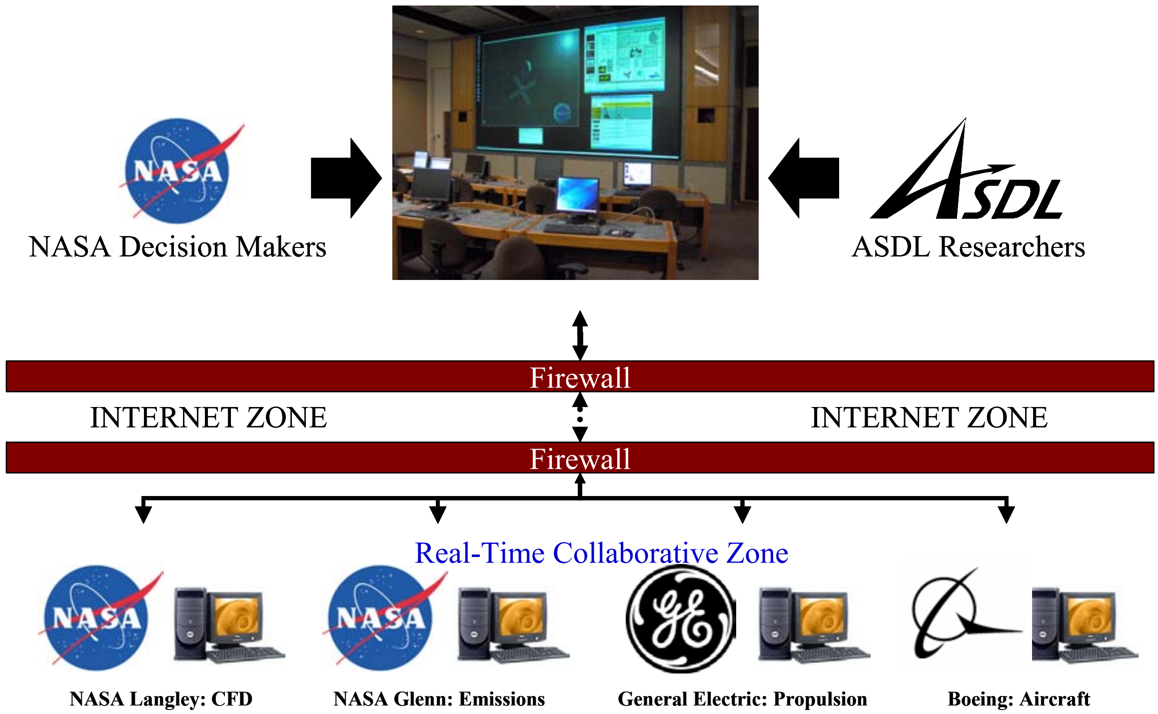


**Figure 15: Notional Example of Collaborative, Multi-Site Design Using the CoVE.**

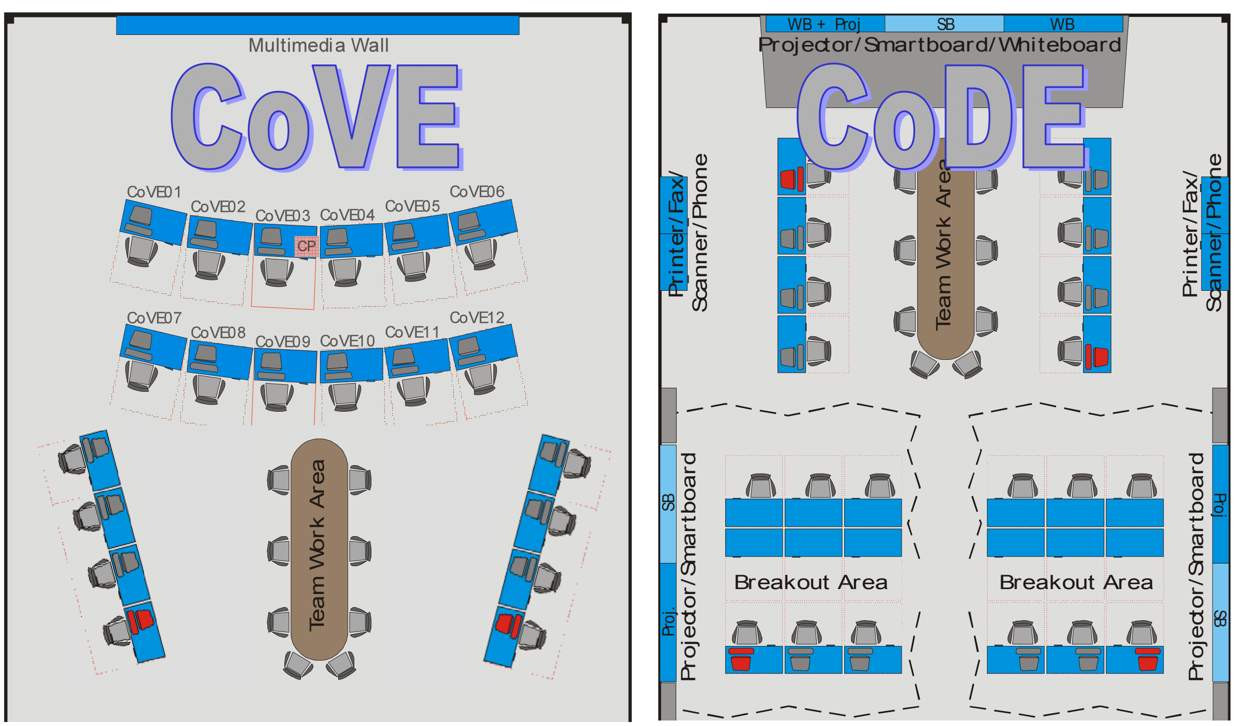


**Figure 16: Collaborative Visualization Environment (CoVE) and Collaborative Design Environment (CoDE).**